Sādhanā Vol. 41, No. 10, October 2016, pp. 1235–1244
DOI 10.1007/s12046-016-0549-9

Mechanical and thermal properties of prepacked aggregate concrete incorporating palm oil fuel ash

HOSSEIN MOHAMMADHOSSEINI[1,*], A S M ABDUL AWAL[2] and ABDUL RAHMAN MOHD SAM[1]

[1]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia
[2]Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Malaysia
e-mail: hofa2018@yahoo.com; asmawal@yahoo.com; abdrahman@utm.my

MS received 11 March 2016; revised 2 May 2016; accepted 17 May 2016

Abstract. Prepacked aggregate concrete (PAC) is a special type of concrete which is made by placing coarse aggregate in a formwork and injecting a grout either by pump or under the gravity force to fill the voids. Use of pozzolanic materials in conventional concrete has become increasingly extensive, and this trend is expected to continue in PAC as well. Palm oil fuel ash (POFA) is one of these pozzolanic ash, which has been recognized as a good pozzolanic material. This paper presents the experimental results of the performance behaviour of POFA in developing physical and mechanical properties of prepacked aggregate concrete. Four concrete mixes namely, prepacked concrete with 100% OPC as a control, and PAC with 10, 20 and 30% POFA were cast, and the temperature growth due to heat of hydration and heat transfer in all the mixtures was recorded. It has been found that POFA significantly reduces the temperature rise in prepacked aggregate concrete and delay the transfer of heat to the concrete body. The compressive and tensile strengths, however, increased with replacement up to 20% POFA. The results obtained and the observation made in this study suggest that the replacement of OPC by POFA is beneficial, particularly for prepacked mass concrete where thermal cracking due to extreme heat rise is of great concern.

Keywords. Prepacked aggregate concrete; palm oil fuel ash; heat of hydration; heat transfer; mechanical properties.

1. Introduction

Prepacked aggregate concrete (PAC) or two-stage concrete drives its name from the unique placement method by which it is made. The prepacked aggregate concrete unlike conventional concrete, is a method of concreting in which the coarse aggregate is first placed in the formwork and then filling the gaps between aggregates by injecting a prepared grout of sand, cement and water [1–3]. Usually, the PAC grouting process can be carried out by two methods i.e. gravity and pumping. In the gravity method, the grout penetrates through the aggregates from the top surface to the bottom of the formwork under its own weight and mostly useful for grouting concrete sections with a depth up to 300 mm [4]. In the pumping method, the mixed grout is pumped from the bottom of the mould into the aggregates through a pipe [5, 6]. The prepacked aggregate concrete has proved particularly useful for plain or reinforced concrete in a number of applications like underwater construction, concrete and masonry repair, for applications where the reinforcement is very complicated, works where placement by normal traditional methods is difficult, large mass concrete where low cement content and low heat of hydration are required [1, 3].

When cement is hydrated, the compounds react with water to acquire stable, low-energy state, and the process is accompanied by the release of energy in the form of heat. The quantity of heat evolved upon complete hydration of a certain amount of unhydrated cement at a given temperature is defined as heat of hydration [7, 8]. The temperature of concrete mix due to hydration process is mainly controlled by materials, mix properties and by environmental factors. The heat of hydration is also related to the chemical composition of the cement. The major component of Portland cement is calcium; therefore the expansion of total heat will be affected by the amount of calcium in the cement. High cement content may be useful to obtain higher strengths of concrete at early ages, but the larger heat generated due to the chemical reactions causes undesirable durability problems like shrinkage and thermal cracks in the concrete [9, 10].

*For correspondence

To decrease the heat of hydration and its harmful effects on the properties of concrete, the use of pozzolanic materials as a conventional replacement in reducing the heat of hydration of concrete is well recognized [10, 11]. The first use of fly ash was made in 1950 at the Otto Holden Dam on the Ottawa River near Mattwa, Ontario [12] and it has been observed that concrete containing 30% fly ash obtained 30% lower temperature than that of plain concrete. The addition of higher volume of fly ash in concrete has been observed to be helpful in many features of durability due to heat liberation [13]. Other types of pozzolanic materials like slag, silica fume and rice husk ash have been revealed to influence the concrete by lowering the heat in massive concrete [11, 13–15].

The manufacture of concrete made by the prepacked method is different from normal traditional concrete, not only in the way of placement, but also it contains a more amount of coarse aggregate and the grout components [3]. With the development of concreting techniques and materials, utilization of different pozzolanic materials in concrete construction has also been increased. These pozzolanic materials are used in the concrete industry for their technical, economic and ecological benefits. One of the latest inclusion in the ash family is palm oil fuel ash (POFA). POFA is an agro-industrial waste that contains a great quantity of activated silica. It is a byproduct of thermal power plants in which palm oil kernel shell and husk are burnt in palm oil mills as fuel. Amongst the oil palm growing countries in Southeast Asia, Malaysia is the second largest producer of palm oil and palm oil products in the world. In 2007, approximately 3 million tons of palm oil fuel ash have been generated in Malaysia, and this production rate is expected to rise due to the increased plantation of palm oil trees [16–18].

It is widely accepted that the conductivity and the heat transfer coefficient have a relatively greater influence on the temperature gradient along with the concrete structure. Heat transfer of concrete is greatly affected by mixing proportion, aggregate type and cementitious particles. In contrast to other thermal properties, such as thermal conductivity and the specific heat of the concrete, however, few studies are available [19–23].

The replacement of ordinary portland cement (OPC) by POFA in the prepacked aggregate concrete is a new area of research, which is gaining significant attention. Although, a number of research works are ongoing on the use of POFA in conventional concrete, there is no literature available concerning the heat transfer property of PAC containing POFA. In this study, concrete specimens were placed in a water tank that contains a heater to boil the water. The heat transfer data were collected based on the difference in temperature of the water and inner side of the concrete specimens.

In view of the utilization of POFA as a supplementary cementing material to prepare grout in prepacked aggregate concrete, extensive research works have been carried out in the Faculty of Civil Engineering, Universiti Teknologi Malaysia, in examining various properties of prepacked aggregate concrete. This paper presents experimental results on the effect of palm oil fuel ash in reducing the heat of hydration and strength properties of the concrete.

2. Materials and test methods

2.1 *Collection and preparation of POFA*

POFA is an agro-industrial waste that contains a great quantity of activated silica. It is a byproduct of thermal power plants in which palm oil kernel shell and husk are burnt in palm oil mills as fuel. In this study, POFA was obtained from a factory in Johor, southern state of Malaysia. The collection of ash was done at the foot of the flue tower where all the fine ashes are trapped, while escaping from the burning chamber of the boiler. After collection, the raw POFA was dried in an oven at a temperature of 110°C for 24 h. Later, it was sieved through 300-μm sieve to remove large particles and other impurities and reduce the carbon content to prevent glassy phase of crystallization. To increase fineness, the ashes were then ground in a modified Los Angeles abrasion test machine having 10 stainless steel bars of 12 mm diameter and 800 mm long.

2.2 *Properties of POFA*

POFA is grey in colour that becomes darker with increasing amounts of unburnt carbon content. The particles have an extensive range of sizes, but they are relatively spherical. A typical electron micrograph of POFA is demonstrated in figure 1. The physical properties and chemical composition of OPC and POFA are presented in table 1. It can be observed that POFA have a higher Blaine fineness and lower specific gravity as compared to OPC. The chemical composition suggests that POFA contains low calcium oxide and may be classified between class F and class C

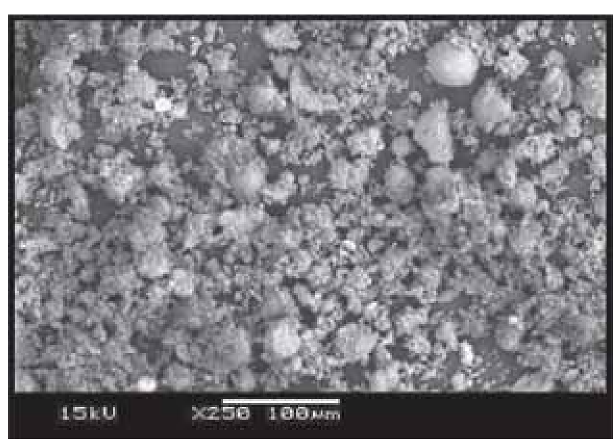

Figure 1. Scanning electron micrograph of POFA.

Table 1. Physical properties and chemical composition of OPC and POFA.

	Physical properties			Chemical composition (%)							
Material	Specific gravity	Blaine fineness	Soundness	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	LOI
OPC	3.15	3990	1.0	20.4	5.2	4.19	62.4	1.55	0.005	2.11	2.36
POFA	2.42	4930	2.0	62.6	4.65	8.12	5.7	3.52	9.05	1.16	6.25

Table 2. Mix proportion of PAC samples.

	Proportion by weight (kg/m^3)					
Mix	Water	Cement	POFA	SP	Fine aggregate	Coarse aggregate
OPC	189	378	–	3.78	548	1321
10% POFA	189	340	37.8	3.78	548	1321
20% POFA	189	302	75.6	3.78	548	1321
30% POFA	189	265	113.4	3.78	548	1321

according to the ASTM C618 [24]. It is interesting to note that the present-day classification system for grouping of ashes into class N, class F and class C is not adequate to appraise their total usefulness, particularly for agricultural ashes. Considering the origin and type, this ash is, however, neither of class C nor of class F.

2.3 *Concrete materials*

The selection of coarse aggregate is of great importance with respect to the prepacked aggregate concrete. Because the applied stresses in prepacked aggregate concrete are transferred first to the coarse aggregate particles and then to the hardened grout [1, 3]. According to ACI 304.1 [25], the coarse aggregate used in prepacked aggregate concrete should be washed, free of surface dust and impurities, and chemically steady to attain a high bond with the grout. The coarse aggregate used in this study was angular and irregular crushed granite with specific gravity of 2.7, having 0.5% water absorption and the size of 20–38 mm. A saturated surface dry mining sand with a fineness modulus of 2.3, 100% passing through ASTM sieve no. 14 having specific gravity and water absorption of 2.6 and of 0.70% respectively was used as fine aggregate. OPC (ASTM Type I) was used in the study. RHEOBUILD 1100 (HG), a polymer based superplasticizer was used to improve fluidity of grout mixture.

2.4 *Mix proportions*

The mix proportions of the grout were prepared at water-binding (w/b) ratios of 0.50 and cement to sand (c/s) ratio of 1/1.5. Superplasticizer was used to improve flow ability of grout by 1% weight of the binder. In this study, the mixture proportions of the grout were determined according to the ASTM C938 [26]. A total of four mixes were made: one with OPC alone as a control and the others with OPC replaced by weights of 10, 20 and 30% POFA. The relative mix proportions of PAC mixes are given in table 2.

2.5 *Preparation of specimens*

The casting of prepacked aggregate concrete occurs in two stages, placing the coarse aggregate in the mould and injecting the grout to fill the gaps between the aggregate particles. The cylinder with unplasticized polyvinyl chloride (UPVC) tubes having 150 mm diameter were placed on a plywood formwork base, the details of which are shown in figure 2(a). To ensure uniform rise of grout across the section in the tube, a cone was attached to the platform under each tube. The cone was made from mild steel and contained a steel ball, placed at the bottom of the cone to act as a one way valve. After placing the coarse aggregate in the tube, it was capped with a perforated plywood cap, which allowed the entrapped air to escape from the tube, while also restraining the top portion of the coarse aggregate from the lifting during the grouting process.

In the second stage, the grout was injected into the gaps of the coarse aggregate by pump and gravity methods. The mixing of the grout was prepared by an electric mixer which took about 5 min to get the desired grout of well consistency [1]. When the POFA was used in the grout, it was first blended with dry OPC before adding water. In the case of superplasticizer, it was added at the time of final mixing of the grout.

Finally, after mixing the grout, the whole mass was transferred into the grout hopper and was stirred continuously, while grouting was in progress to avoid any segregation in the grout mixture. The hand pump, connected to the grout hopper, was used to inject the grout through the

Figure 2. Grouting methods of prepacked aggregate concrete: (**a**) pump and (**b**) gravity.

aggregates into the tubes. As the tube was full, grout pumping was stopped and the time taken to fill the tube was recorded. The average time required to fill the 2000 mm long tube was about 120 s. In the gravity method, grout was injected into the cylindrical mould through a PVC pipe under gravitational force, as shown in figure 2(b). After 24 h of casting, the concrete specimens were demoulded and immersed into the water tank until the test. All the tests were performed at an average room temperature of 27°C with the relative humidity (RH) of 80 ± 5%.

2.6 *Method of testing*

The effect of POFA content at a different percentage on grout consistency were studied to investigate the flow characteristics of the grout (figure 3) according to ASTM C939 [27]. Measurement of bleeding was done according to ASTM C940 [28]. Grout with a volume of 800 ± 10 ml, was poured inside a 1000 ml glass graduate for various POFA contents of 0, 10, 20 and 30% mix proportions to measure the bleeding of the grout mixture. Cube specimens with dimensions of 70 × 70 × 70 mm were made to determine the 28 days dry density of the different grout mixtures. The compressive and splitting tensile strength tests were conducted with 150 mm × 300 mm cylinder specimens according to ASTM C39 [29] and ASTM C496 [30] respectively.

2.7 *Measurement of heat of hydration*

Fundamentally, heat of hydration is the property of cement concrete or mortar in its hardening state. In this study, cubical plywood with sides 280 mm was internally insulated the pack with 76 mm thick and expanded polystyrene

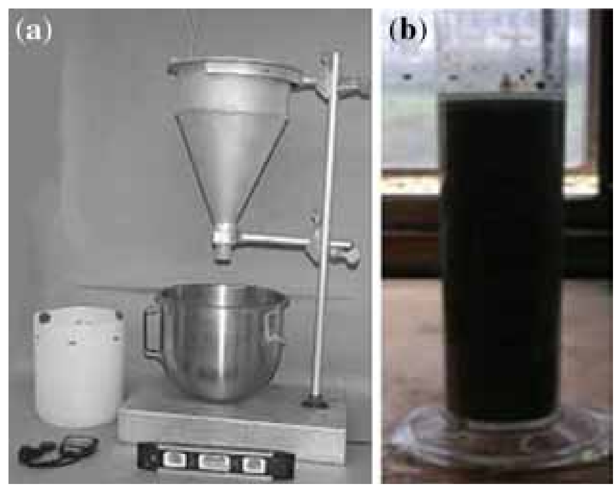

Figure 3. (**a**) Grout fluidity test. (**b**) Bleeding of grout test.

acting as the insulator. Concrete mix with 100% OPC and those with OPC replaced by 10, 20 and 30% by weight were cast into the cylinder mould of 150 mm diameter and 300 mm height. Prior to casting, a thermocouple (Type K) was inserted into the center of each sample and, the cylinder was filled only with coarse aggregates and grout injected into the mould through the drilled hole of the polypropylene foam lid and was connected to a computer driven data acquisition system. An insulated cubical box and the test arrangement are illustrated in figure 4. When grout was poured into the mould, heat was liberated by hydration process and subsequently increased the temperature of the prepacked aggregate concrete mass. This rise in temperature and succeeding drop was observed with a close interval during the first 24 h and lesser frequency afterwards until the temperature dropped close to the initial reading. The measurement of temperature was continued up to 140 h for all the mixes.

2.8 *Heat transfer procedure*

Heat transfer test was conducted on cylinder specimen of 150 mm diameter and 300 mm height, which was used for the heat of hydration test at the age of 28 days. To avoid any penetration of water into the concrete, all PAC specimens were covered with a thin plastic sheet. To protect the thermocouple against sudden impacts, a PVC pipe with 2 cm diameter was used (figure 5). All samples kept in the water tank at the initial water temperature of about 34°C and the same was recorded. Further, the temperature of water gradually raised up to 100°C and the measurement of temperature was continued for all the mixes.

3. Results and discussion

3.1 *Properties of grout*

The basic properties of the grout in the manufacture of prepacked aggregate concrete are its flow characteristics i.e. grout consistency and bleeding properties. The test results are displayed in table 3. In the investigation of grout consistency, the effects of different percentages of POFA content with 1% superplasticizer on the fluidity of grout were studied.

Figure 4. Test setup for the measurement of heat of hydration.

Figure 5. Heat transfer test arrangement: (**a**) boiler water tank and (**b**) PAC sample.

Table 3. Properties of grout and prepacked aggregate concrete

Mix	Grout fluidity (s)	Bleeding (%)	Density (kg/m^3)	28-day compressive strength (MPa)		28-day tensile strength (MPa)	
				Pump	Gravity	Pump	Gravity
OPC	15.3	10.38	2145	33.0	32.6	2.9	2.8
10% POFA	13.9	9.13	2130	35.1	32.9	3.2	2.9
20% POFA	12.8	8.63	2120	33.8	33.2	2.9	2.8
30% POFA	12.1	8.00	2115	28.7	24.9	2.7	2.6

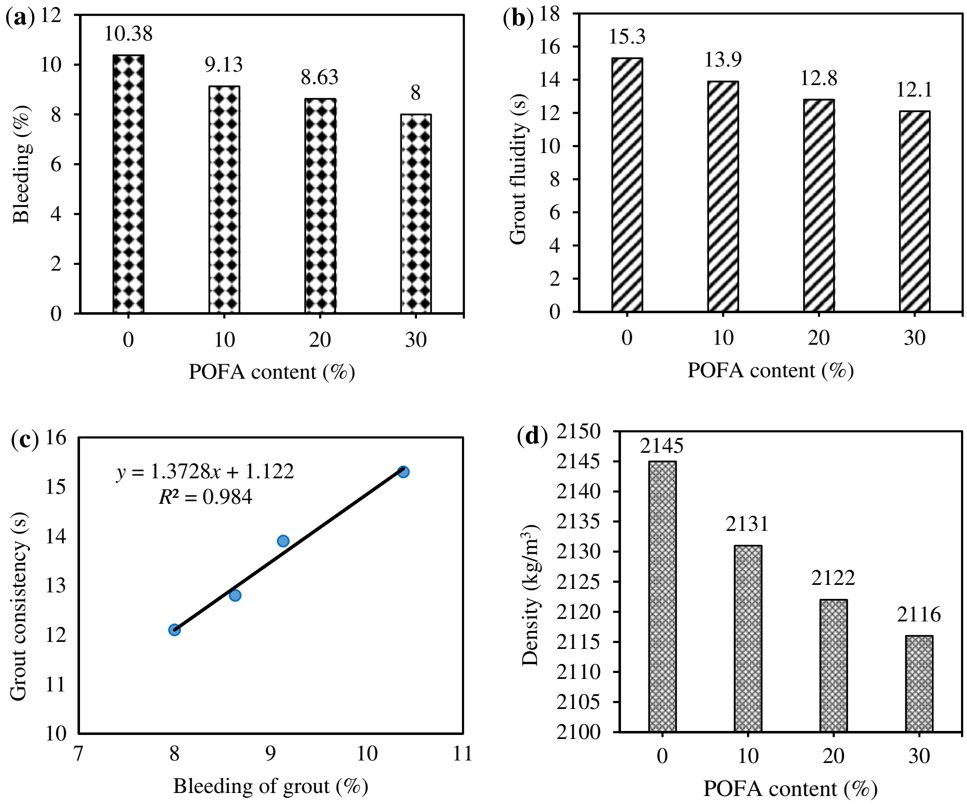

Figure 6. Properties of fresh grout (**a**) bleeding, (**b**) fluidity, (**c**) relationship between the grout fluidity and bleeding of grout and (**d**) density.

From the results, it is noted that as the POFA content increases, the fluidity of the grout also increases. At w/b and c/s ratios of 0.5 and 1.15 respectively, the 10% replacement presented fluidity of 13.9 s, whereas the 30% replacements exhibited a value of 12.1 for the same w/b and c/s ratios as compared to that of 15.3 s for OPC grout. Figure 6 reveals that the bleeding of grout mixes containing POFA was relatively less than that of OPC grout. The bleeding capacity of grout which is the ratio of the bleed water to mixing water, for OPC grout with a w/b ratio of 0.5, for example, was 10.38%, whereas the bleeding capacity of the grouts containing 10, 20 and 30% POFA for the same w/b ratio was 9.13, 8.63 and 8.0% respectively. This shows that the POFA used on the grout to mix, reduced the amount of bleeding significantly. The dry density of the OPC and POFA grout mixes is illustrated in figure 6. It was found that the density of the grout mixes containing POFA was lower than that in OPC mix. This is expected due to the lower specific gravity of POFA (2.42) particle compared to OPC (3.15). For instance, the lowest density of 2116 kg/m^3 was obtained for the grout containing 30% POFA which is 1.5% lower than that of 2145 kg/m^3 for grout with OPC only. Similar trends have been reported in normal concrete containing POFA [18, 31].

Figure 6 also shows the relationship between the grout consistency and bleeding of grout of prepacked aggregate concrete. A direct relationship between the fresh properties of the grout can be clearly observed in this figure. A linear regression method was used to correlate the experimental data with a coefficient of determination, $R^2 = 0.91$ and $R^2 = 0.984$ for a prediction model for the properties of fresh grout.

3.2 *Compressive and splitting tensile strengths*

The investigation of the strength of prepacked aggregate concrete for pump and gravity methods was carried out at the age of 28 days. The compressive strength data given in table 3 reveal that using up to 20% POFA in the grout, the compressive strength of PAC was found to be higher than that of OPC for both pump and gravity samples. Figure 7 shows that the highest value of 35.10 MPa compressive strength was obtained in the pumped prepacked aggregate concrete with 10% POFA, while sample with 20% POFA content showed 33.85 and 33.20 MPa compared to that values of 33.00 and 32.60 MPa for pump and gravity OPC PAC concretes respectively. Further increase in POFA content, however, reduced the strength of concrete made by both pump and gravity methods.

The splitting tensile strength of prepacked aggregate concrete filled with a pump and gravity methods was also investigated at the age of 28 days. The test results presented in table 3 revealed that higher the amount of POFA, lower the tensile strength value. For example, the highest strength

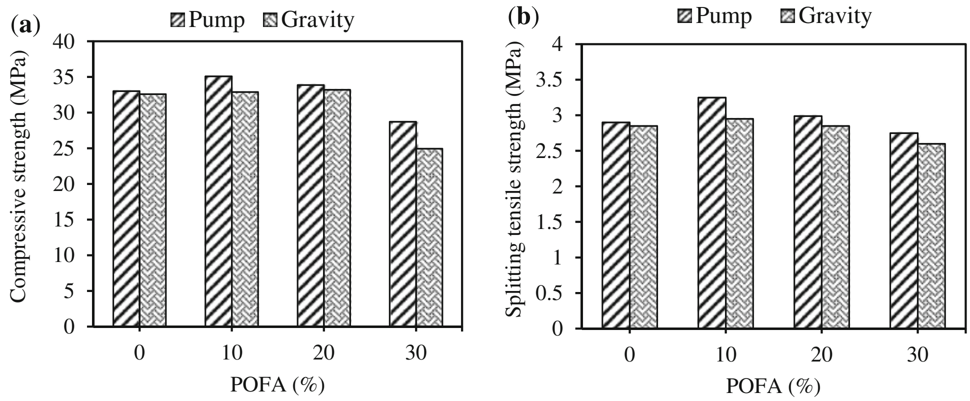

Figure 7. (**a**) Compressive and (**b**) tensile strength of PAC at 28 days.

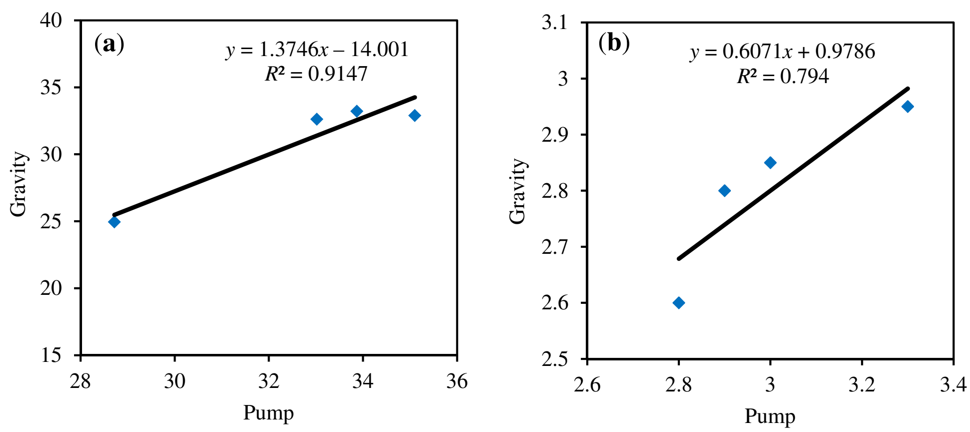

Figure 8. Relationship between the gravity and pump methods of (**a**) compressive strength and (**b**) tensile strength.

of 3.25 MPa was recorded for 10% POFA mix filled by pump, whereas a value of 2.90 MPa was obtained for PAC containing OPC alone for the same method. A lowest tensile strength of 2.75 MPa was, however, recorded for specimen containing 30% POFA having a 0.50 w/b ratio, which is around 5% lower than that of PAC with OPC alone.

Figure 8 reveals the relationship between compressive strength and splitting tensile strength of gravity and pump methods of prepacked aggregate concrete at the age of 28 days. A direct relationship between the compressive and tensile strength of two methods can clearly be observed in these figures. A linear regression method was applied to correlate the experimental data resulting in the Eqs. (1) and (2), with a coefficient of determination $R^2 = 0.91$ and 0.79 respectively.

$$f_{cg} = 1.3746 f_{cp} - 14.001; \quad (1)$$

$$f_{tg} = 0.6368 f_{tp} + 0.9172, \quad (2)$$

where f_{cg} is the compressive strength of gravity method, f_{cp} is the compressive strength of pump method, f_{tg} is the tensile strength of gravity method and f_{tp} is the tensile strength of pump method.

3.3 *Heat of hydration*

The time–temperature histories of different prepacked aggregate concrete mixes are displayed in table 4 and the growth of temperature due to heat liberation during the hydration process obtained at the center of insulated PAC specimens of all the concrete mixes is shown in figure 9. It can be seen that initially, the temperature increased almost equally in all mixes. However, with the increase in time, the effect of the replacement of OPC with POFA can absolutely be noticed. The PAC with grout containing POFA reduced the total temperature rise and furthermore, it delayed the time to reach the peak temperature.

Table 4. Characteristics of heat of hydration of OPC and POFA prepacked aggregate concrete.

Properties	OPC	10% POFA	20% POFA	30% POFA
Initial temperature (°C)	28.0	28.2	28.1	27.8
Peak temperature (°C)	45.2	43.0	42.1	40.2
Time since mixing to peak temperature (h)	19.5	22.0	24.0	26.0
Relative reduction in peak temperature (%)	0.0	5.0	7.0	11.0

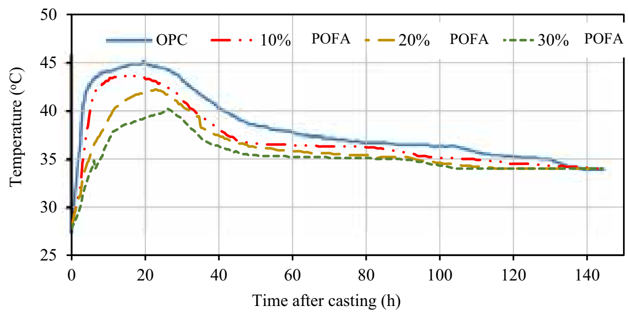

Figure 9. Development of temperature in prepacked aggregate concrete mixes.

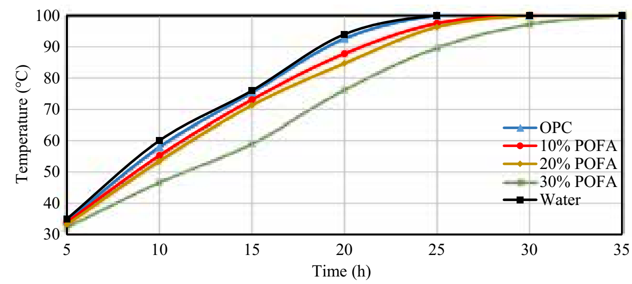

Figure 10. Influence of POFA content on heat transfer of PAC in boiling water.

A peak temperature of 45.2°C was recorded for PAC having OPC grout in 20 h after grout injected, while 43 and 42.1°C were observed in 10 and 20% POFA concrete respectively. A peak temperature of 40.2°C was, however, recorded for 30% POFA concrete at 28 h after grout injecting. Both the OPC and POFA grouts ultimately exposed a slow drop in temperature until a relatively steady state was reached during the test. The reduction in the heat of hydration of mixes can be due to the lower amount of calcium oxide (CaO) in OPC due to the replacement of POFA. In terms of peak temperature and the time to reach at this temperature, grouts containing POFA performed better that that containing OPC alone. A similar tendency has been reported by Abdul Awal and Shehu [8], who observed a reduction in temperature in normal concrete containing high volume POFA from that in OPC normal concrete. The obtained results are also in agreement with Chandara *et al* [32], who found out that total heat of hydration of blended cement pastes containing POFA is lower than OPC paste. Therefore, to reduce the heat of hydration and avoid the thermal cracks in massive pre-packed aggregate concrete, utilization of POFA can be a good solution of this kind.

3.4 *Heat transfer*

In conduction, heat is transferred from a hot temperature body to a cold body temperature. The transfer of heat will continue as long as there is a difference in temperature between the two bodies. Once the two locations have reached the same temperature, thermal equilibrium is established and the heat transfer stops. Thermal mass is a term that describes the ability of a material to store heat; which various construction materials can do to a greater or lesser extent. But, to be beneficial in the built environment, they must also be able to absorb and release heat at a rate roughly in step-wise with a structure's daily heating and cooling cycle. Concrete and masonry products do this well and, being dense materials, can also store a lot of heat [7].

The objective of this test was to demonstrate that the time–heat to transfer different PAC mixes at mid depth of concrete specimens during boiling of the water and the test results are illustrated in figure 10. It has been observed that the temperature of water and PAC specimen with OPC reached to 100°C almost at the same time at 25 h after test initiated. But for prepacked aggregate concrete samples containing POFA, the rate of transfer of heat was obtained to be lower than that of OPC and PAC, and the effect of the POFA content can be absolutely detected. It is interesting to note that the effect of higher POFA content on the delay of time at which the specimen reached to the 100°C was more significant than that of lower POFA content and OPC concrete alone.

The information presented in figure 8 depicts that although the rate of transfer of heat of all mixes containing POFA was significantly lower, considerably higher rate was evolved for OPC concrete. A maximum time to reach 100°C was observed for 30% POFA prepacked aggregate concrete at 35 h, while 10 and 20% POFA concrete reached at 30 h after the test started. It is generally known that the smaller the particle size, the greater the surface area-to-volume ratio, and thus, the more dense concrete and less voids. The effects of greater fineness of POFA on strength are generally seen during the later ages. The pozzolanic nature of POFA aids to provide a denser concrete, therefore, it prevents the entering harmful particles and also delay the time of transfer of heat in the mid center of the concrete specimens. Prepacked aggregate concrete containing POFA obtained a better result in terms of delay of the transfer of heat compared to the OPC prepacked aggregate concrete, therefore, it can be used as an insulated concrete structure.

4. Conclusions

The performance of PAC containing POFA has been outlined in this paper. It has been found that the highest grout consistency based on the flow cone test belonged to grout with 30% POFA. Higher replacement of OPC by POFA resulted in lower bleeding and density of the grout. It has been also found that the grout containing POFA increased the compressive and tensile strength of prepacked aggregate concrete and these values are higher in the pump method than that of gravity method.

The experimental results in this study further demonstrate that POFA has good potentials in controlling and reducing the heat of hydration of PAC. Although, the maximum strength was obtained for 10% POFA replacement, higher volume replacement of OPC by POFA is advantageous, particularly for mass prepacked aggregate concrete, where thermal cracking due to extreme heat rise is of great concern. Inclusion of POFA, in general, reduced the heat transfer property of the prepacked aggregate concrete.

Acknowledgements

The authors wish to acknowledge the help and cooperation received from the technical staff of Structure and Materials Laboratory of the Universiti Teknologi Malaysia (UTM) in conducting the experimental work.

References

[1] Awal A S M A 1984 *Manufacture and properties of prepacked aggregate concrete*. Master thesis, University of Melbourne, Australia
[2] Abdelgader H 1995 *Experimental–mathematical procedure of designing the two-stage concrete*. Ph.D. Dissertation, Technical University of Gdañsk, Gdañsk, Poland
[3] Najjar M, Soliman A and Nehdi M 2014 Critical overview of two-stage concrete: Properties and applications. *Constr. Build. Mater.* 62: 47–58
[4] Champion S and Davis L 1958 Grouted concrete construction. *Reinf. Concrete Rev.* 569–608
[5] Abdelgader H 1999 How to design concrete produced by a two-stage concreting method. *Cement Concrete Res.* 29: 331–337
[6] O'Malley J and Abdelgader H 2010 Investigation into viability of using two-stage (pre-placed aggregate) concrete in Irish setting. *Front. Architect. Civil Eng. China* 4(1): 127–132
[7] Neville A M 1995 *Properties of concrete*, 4th edition, Longman Group Ltd, England
[8] Awal A S M A and Shehu I 2013 Evaluation of heat of hydration of concrete containing high volume palm oil fuel ash. *Fuel* 105: 728–731
[9] Awal A S M A and Shehu I 2015 Performance evaluation of concrete containing high volume palm oil fuel ash exposed to elevated temperature. *Constr. Build. Mater.* 76: 214–220
[10] Ballim Y and Graham P 2009 The effects of supplementary cementing materials in modifying the heat of hydration of concrete. *Mater. Struct.* 42: 803–811
[11] Langan B, Weng K and Ward M 2002 Effect of silica fume and fly ash on heat of hydration of Portland cement. *Cement Concrete Res.* 32: 1045–1051
[12] Sturrup V, Hooton R and Clendenning T 1983 Durability of fly ash concrete. In: *1st International conference on fly ash, silica fume, slag and other mineral by products in concrete*, Montebello
[13] Malhotra V 1994 CANMET investigations dealing with high-volume fly ash concrete. *Adv. Concrete Technol.* 445–482
[14] Mehta P and Pirtz D 1978 Use of rice husk ash to reduce temperature in high-strength mass concrete. *ACI J Proc.* 75(2): 60–63
[15] Tangchirapat W, Saeting T, Jaturapitakkul C, Kiattikomol K and Siripanichgorn A 2007 Use of waste ash from palm oil industry in concrete. *Waste Manag.* 27: 81–88
[16] Mohammadhosseini H, Awal ASMA and Ehsan AH 2015 Influence of palm oil fuel ash on fresh and mechanical properties of self-compacting concrete. *Sadhana* 40(6): 1989–1999
[17] Bamaga S, Hussin M and Ismail M 2013 Palm oil fuel ash: Promising supplementary cementing materials. *KSCE J. Civil Eng*. 17(7): 1708–1713
[18] Johari M M, Zeyad A, Bunnori N and Ariffin K 2012 Engineering and transport properties of high-strength green concrete containing high volume of ultrafine palm oil fuel ash. *Constr. Build. Mater.* 30: 281–288
[19] Khan M 2002 Factors affecting the thermal properties of concrete and applicability of its prediction models. *Build. Environ.* 37: 607–614
[20] Kima K, Jeon S, Kim J and Yang S 2003 An experimental study on thermal conductivity of concrete. *Cement Concrete Res.* 33: 363–371
[21] Demirboğa R 2007 Thermal conductivity and compressive strength of concrete incorporation with mineral admixtures. *Build. Environ.* 42: 2467–2471
[22] Lee Y, Choi M S, Yi S T and Kim J K 2009 Experimental study on the convective heat transfer coefficient of early-age concrete. *Cement Concrete Composit.* 31: 60–71
[23] Guo L, Zhong L and Zhu Y 2011 Thermal conductivity and heat transfer coefficient of concrete. *J. Wuhan Univ. Technol. Mater. Sci.* 26(4): 791–796
[24] ASTM C618 2015 *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*. ASTM International
[25] ACI 304.1 2005 *Guide for the use of preplaced aggregate concrete for structural and mass concrete applications*. American Concrete Institute, ACI Committee

[26] ASTM C938 2010 *Standard practice for proportioning grout mixtures for preplaced-aggregate concrete*. ASTM International

[27] ASTM C939 2010 *Standard test method for flow of grout for preplaced-aggregate concrete (flow cone method)*. ASTM International

[28] ASTM C940 2010 *Standard test method for expansion and bleeding of freshly mixed grouts for preplaced-aggregate concrete in the laboratory*. ASTM International

[29] ASTM C39 2014 *Standard test method for compressive strength of cylindrical concrete specimens*. ASTM International

[30] ASTM C496 2011 *Standard test method for splitting tensile strength of cylindrical concrete specimens*. ASTM International

[31] Tangchirapat W, Jaturapitakkul C and Chindaprasirt P 2009 Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete. *Constr. Build. Mater.* 23: 2641–2646

[32] Chandara C, Mohd Azizli K, Ahmad Z, Hashim S and Sakai E 2012 Heat of hydration of blended cement containing treated ground palm oil fuel ash. *Constr. Build. Mater.* 27: 78–81